spectroradiometry and equipment. Thanks are also given to the staffs of the NIST Calibration Program and NVLAP for their help with the measurement service. In particular thanks go to Janet Land of the Precision Engineering Division and Carroll Brickenkamp of the Measurement Services office for their help with quality systems and documentation.

12. References

[1] American National Standard for Calibration - Calibration Laboratories and Measuring and Test Equipment - General Requirements, ANSI/NCSL Z540-1-1994. (Currently available through the National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301.)

[2] Determination of the Spectral Responsivity of Optical Radiation Detectors, Publ. 64 (Commission Internationale de L'Éclairage, Paris, 1984). (Currently available through the U. S. National Committee of the CIE, c/o Mr. Thomas M. Lemons, TLA-Lighting Consultants, Inc., 72 Loring Avenue, Salem, MA 01970.)

[3] W. Budde, *Optical Radiation Measurements, Volume 4: Physical Detectors of Optical Radiation*, Academic Press, Inc., Orlando, FL (1983) pp. 38-59.

[4] J. Geist, L. B. Schmidt, and W. E. Case, "Comparison of the Laser Power and Total Irradiance Scales Maintained by the National Bureau of Standards," *Appl. Opt.* **12**, 2773-2776 (1973).

[5] J. Geist, M. A. Lind, A. R. Schaefer, and E. F. Zalewski, "Spectral Radiometry: A New Approach Based on Electro-Optics," Natl. Bur. Stand. (U.S.), Tech. Note 954 (1977).

[6] Unpublished preprint of sequel to NBS Technical Note 950 describing the radiometric characteristics of the DRTIP radiometers, p. 9.

[7] B. N. Taylor and C. E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, Natl. Inst. Stand. Technol., Tech. Note 1297 (1994 ed.).

[8] E. F. Zalewski and J. Geist, "Silicon Photodiode Absolute Spectral Response Self-Calibration," *Appl. Opt.* **19**, 1214-1216 (1980).

[9] J. Geist, E. F. Zalewski, and A. R. Schaefer, "Spectral Response Self-Calibration And Interpolation of Silicon Photodiodes," *Appl. Opt.* **19**, 3795-3799 (1980).

[10] E. F. Zalewski and C. R. Duda, "Silicon Photodiode Device with 100 % External Quantum Efficiency," *Appl. Opt.* **22**, 2867-2873 (1983).

[11] The QED-200 is now manufactured by UDT Instruments (formerly Graseby Optronics), Orlando, FL.

[12] E. F. Zalewski, The NBS Photodetector Spectral Response Calibration Transfer Program, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-17, p. 45 (1988).

[13] J. M. Houston and E. F. Zalewski, "Photodetector Spectral Response Based on 100 % Quantum Efficient Detectors," *Optical Radiation Measurements II*, James M. Palmer, Editor, Proc. SPIE 1109, pp. 268-277 (1989).

[14] C. L. Cromer, "A New Spectral Response Calibration Method using a Silicon Photodiode Trap Detector," presented at the 1991 Measurement Science Conference, Anaheim, CA, Jan. 31-Feb. 1, 1991 (unpublished).

[15] N. P. Fox, "Trap Detectors and Their Properties," *Metrologia* **28**, 197-202 (1991).

[16] J. Geist, "Current Status of, and Future Directions In, Silicon Photodiode Self-Calibration," *Optical Radiation Measurements II*, James M. Palmer, Editor, Proc. SPIE 1109, 246-256 (1989).

[17] E. F. Zalewski and C. C. Hoyt, "Comparison Between Cryogenic Radiometry and the Predicted Quantum Efficiency of pn Silicon Photodiode Light Traps," *Metrologia* **28**, 203-206 (1991).

[18] N. P. Fox, "Radiometry with Cryogenic Radiometers and Semiconductor Photodiodes," *Metrologia* **32**, 535-543 (1995/96).

[19] A. C. Parr, A National Measurement System for Radiometry, Photometry, and Pyrometry Based Upon Absolute Detectors, Natl. Inst. Stand. Technol., Tech. Note 1421 (1996).

[20] T. R. Gentile, J. M. Houston, J. E. Hardis, C. L. Cromer, and A. C. Parr, "National Institute of Standards and Technology High-Accuracy Cryogenic Radiometer," *Appl. Opt.* **35**, 1056-1068 (1996).

[21] T. R. Gentile, J. M. Houston, and C. L. Cromer, "Realization of a Scale of Absolute Spectral Response Using the National Institute of Standards and Technology High-Accuracy Cryogenic Radiometer," *Appl. Opt.* **35**, 4392-4403 (1996).

[22] T. C. Larason, S. S. Bruce, and C. L. Cromer, "The NIST High Accuracy Scale for Absolute Spectral Response from 406 nm to 920 nm," *J. Res. Natl. Inst. Stand. Technol.* **101**, 133-140, (1996).

[23] NIST Calibration Services Users Guide, Joe D. Simmons, Editor, Natl. Inst. Stand. Technol., Spec. Publ. 250 (1991).

[24] NIST Calibration Services Users Guide Fee Schedule, Natl. Inst. Stand. Technol., Spec. Publ. 250 Appendix (1997).

[25] H. J. Kostkowski and F. E. Nicodemus, An Introduction to the Measurement Equation, Chapter 5 in Self-Study Manual on Optical Radiation Measurements: Part I--Concepts, Chapters 4 and 5, F. E. Nicodemus, Editor, Natl. Bur. Stand. (U.S.), Tech. Note 910-2 (1978).

[26] H. J. Kostkowski, The Relative Spectral Responsivity and Slit-Scattering Function of a Spectroradiometer, Chapter 7 in Self-Study Manual on Optical Radiation Measurements: Part I--Concepts, Chapters 7, 8, and 9, F. E. Nicodemus, Editor, Natl. Bur. Stand. (U.S.), Tech. Note 910-4 (1979).

[27] R. Köhler, R. Goebel, R. Pello, and J. Bonhoure, "Effects of Humidity and Cleaning on the Sensitivity of Si Photodiodes," *Metrologia* **28**, 211-215 (1991).

[28] A description of diffraction and the Airy disk can be found in most basic optics texts, e.g., F. L. Pedrotti and L. S. Pedrotti, *Introduction to Optics*, 2nd edition, Prentice Hall, Englewood Cliffs, NJ (1993) or E. Hecht, *Optics*, 2nd edition, Addison-Wesley Publishing Company, Reading, MA (1987).

[29] J. B. Shumaker, Introduction to Coherence in Radiometry, Chapter 10 in Self-Study Manual on Optical Radiation Measurements: Part I--Concepts, Chapter 10, F. E. Nicodemus, Editor, Natl. Bur. Stand. (U.S.), Tech. Note 910-6 (1983).

[30] J. L. Gardner, "Astigmatism Cancellation in Spectroradiometry," *Metrologia* **28**, 251-254 (1991).

[31] F. Lei and J. Fischer, "Characterization of Photodiodes in the UV and Visible Spectral Region Based on Cryogenic Radiometry," *Metrologia* **30**, 297-303 (1993).

[32] R. Köhler, R. Goebel, and R. Pello, Report on the International Comparison of Spectral Responsivity of Silicon Detectors, Rapport BIPM-94/9, document CCPR/94-2, dated July 27, 1994, Bureau International des Poids et Mesures, Pavillon de Breteuil, 93212 Sevres, Cedex, France.

[33] J. M. Bridges and W. R. Ott, "Vacuum Ultraviolet Radiometry. 3: The Argon Mini-Arc as a New Secondary Standard of Spectral Radiance," *Appl. Opt.* **16**, 367-376 (1977).

[34] G. Eppeldauer and J. E. Hardis, "Fourteen-Decade Photocurrent Measurements with Large-Area Silicon Photodiodes at Room Temperature," *Appl. Opt.* **30**, 3091-3099 (1991).

[35] W. Budde, *Optical Radiation Measurements, Volume 4: Physical Detectors of Optical Radiation*, Academic Press, Inc., Orlando, FL (1983) pp. 265-268.

[36] G. Eppeldauer, "Electronic Characteristics of Ge and InGaAs Radiometers," *Infrared Technology and Applications XXII*, Björn F. Andresen and Marija Strojnik, Editors, Proc. SPIE 3061, pp. 833-838 (1997).

[37] J. E. Martin, N. P. Fox, and P. J. Key, "A Cryogenic Radiometer for Absolute Radiometric Measurements," *Metrologia* **21**, 147-155 (1985).

[38] At the 1994 CCPR meeting in Paris approximately 10 nations indicated that they had purchased a cryogenic radiometer or were in the process of purchasing one and would use it as the basis of the radiometric measurements in their respective nations.

[39] Electrical standards are maintained in the Electronics and Electrical Engineering Laboratory at NIST.

[40] R. C. Paule and J. Mandel, "Consensus Values and Weighting Factors," *J. Res. Natl. Bur. Stand.* (U.S.) **87**, 5 (1982).

[41] There are several books on optical detectors and radiometry that describe pyroelectric detectors. Many of these books are listed in the bibliography along with the following.

E. L. Dereniak and D. G. Crowe, *Optical Radiation Detectors*, Wiley, New York, NY (1984).

W. Budde, *Optical Radiation Measurements, Volume 4: Physical Detectors of Optical Radiation*, Academic Press, Inc., Orlando, FL (1983).

[42] V. R. Weidner and J. J. Hsia, NIST Measurement Services: Spectral Reflectance, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-8 (1987).

P. Y. Barnes and E. A. Early, NIST Measurement Services: Spectral Reflectance, Natl. Inst. Stand. Technol., Spec. Publ. 250-8 Revised (in preparation).

[43] K. L. Eckerle, J. J. Hsia, K. D. Mielenz, and V. R. Weidner, NIST Measurement Services: Regular Spectral Transmittance, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-6 (1987).

[44] See Ref. 27 and personal communication with one of the authors. Note: Cleaning a photodiode can change its responsivity.

[45] E. M. Gullikson, R. Korde, L. R. Canfield, R. E. Vest, "Stable Silicon Photodiodes for Absolute Intensity Measurements in the VUV and Soft X-Ray Regions," *J. Elect. Spect. Rel. Phenom.* **80**, 313-316 (1996).

[46] K. D. Stock, "Internal Quantum Efficiency of Ge Photodiodes," *Appl. Opt.* **27**, 12-14 (1988).

[47] A. R. Schaefer, E. F. Zalewski, and J. Geist, "Silicon Detector Nonlinearity and Related Effects," *Appl. Opt.* **22**, 1232-1236 (1983).

[48] Private communication with Richard Austin of Gamma Scientific, San Diego, CA.

[49] T. C. Larason and S. S. Bruce, "Spatial Uniformity of Responsivity for Silicon, Gallium nitride, Germanium, and Indium Gallium Arsenide Photodiodes," *Metrologia* (to be published).

[50] E. F. Zalewski, Radiometry and Photometry, Chapter 24 in *Handbook of Optics*, Vol. II, 2nd edition, M. Bass, Editor-in-Chief, McGraw-Hill, New York, NY (1995).

[51] C. L. Wyatt, *Radiometric Calibration: Theory and Methods*, Academic Press, San Diego, CA (1978).

[52] American National Standard for Expressing Uncertainty - US Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997. (Currently available through the National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301.)

[53] A. Corrons and E. F. Zalewski, Detector Spectral Response from 350 to 1200 nm Using a Monochromator Based Spectral Comparator, Natl. Bur. Stand. (U.S.), Tech. Note 988 (1978).

[54] R. D. Saunders and J. B. Shumaker, "Apparatus Function of a Prism-Grating Double Monochromator," *Appl. Opt.* **25**, 3710-3714 (1986).

[55] N. M. Durant and N. P. Fox, "Evaluation of Solid-State Detectors for Ultraviolet Radiometric Applications," *Metrologia* **32**, 505-508 (1995/96).

R. Goebel, R. Köhler, and R. Pello, "Some Effects of Low-Power Ultraviolet Radiation on Silicon Photodiodes," *Metrologia* **32**, 515-518 (1995/96).

G. Eppeldauer, "Longterm Changes of Silicon Photodiodes and Their Use for Photometric Standardization," *Appl. Opt.* **29**, 2289-2294 (1990).

L. R. Canfield, J. Kerner, and R. Korde, "Stability and Quantum Efficiency Performance of Silicon Photodiode Detectors in the Far Ultraviolet," *Appl. Opt.* **28**, 3940-3943 (1989).

R. Korde and J. Geist, "Quantum Efficiency Stability of Silicon Photodiodes," *Appl. Opt.* **26**, 5284-5290 (1987).

K. D. Stock, "Spectral Aging Pattern of Carefully Handled Silicon Photodiodes," *Measurement* **5**, 141-144 (1987).

K. D. Stock and R. Heine, "On the Aging of Photovoltaic Cells," *Optik* (Weimar) **71**, 137-142 (1985).

[56] A. L. Migdall and C. Winnewisser, "Linearity of a Silicon Photodiode at 30 MHz And Its Effect on Heterodyne Measurements," *J. Res. Natl. Inst. Stand. Technol.* **96**, 143-146 (1991).

J. L. Gardner and F. J. Wilkinson, "Response Time and Linearity of Inversion Layer Silicon Photodiodes," *Appl. Opt.* **24**, 1531-1534 (1985).

A. R. Schaefer, E. F. Zalewski, and J. Geist, "Silicon Detector Nonlinearity and Related Effects," *Appl. Opt.* **22**, 1232-1236 (1983).

W. Budde, "Multidecade Linearity Measurements on Si Photodiodes," *Appl. Opt.* **18**, 1555-1558 (1979).

[57] T. C. Larason, "The Radiometric Physics Division's Efforts at Building a Quality System Based on ISO/IEC Guide 25," presented at the Asociacion Mexicana De Metrologia, A. C. 1994 Conference, Acapulco, Mexico May 10-13, 1994 (unpublished).

[58] S. S. Bruce and T. C. Larason, "Building a Quality System Based on ANSI/NCSL Z540-1-1994 - An Effort by the Radiometric Physics Division at NIST," *Proc. NCSL 1995 Workshop and Symposium* (National Conference of Standards Laboratories), Dallas, TX July 16-20, 1995.

[59] S. S. Bruce and T. C. Larason, Developing quality system documentation based on ANSI/NCSL Z540-1-1994 -- the optical technology division's effort, Natl. Inst. Stand. Technol., Internal Report 5866 (1996).

[60] Control charts are discussed in many texts on quality control and statistics, e.g., W. Mendenhall and T. Sincich, *Statistics for Engineering and the Sciences*, 3rd edition, Dellen Publishing Company, San Francisco, CA (1992).

[61] L. R. Canfield, "New Far UV Detector Calibration Facility at the National Bureau of Standards," *Appl. Opt.* **26**, 3831-3837 (1987).

[62] L. R. Canfield and N. Swanson, Far Ultraviolet Detector Standards, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-2 (1987).

[63] NIST is currently upgrading SURF II, creating SURF III. Improvements will be made in many areas, including beam current monitoring, magnetic structure uniformity, and electron energy.

[64] R. Köhler, R. Goebel, and R. Pello, "Results of an International Comparison of Spectral Responsivity of Silicon Photodetectors," *Metrologia* **32**, 463-468 (1995/96).

[65] These values are from the manufacturer's catalog, Photodiodes, Cat. No. KPD 0001E05, Aug. 1996 T, Hamamatsu Photonics K. K., Solid State Division, 1126-1, Ichino-cho, Hamamatsu City, 435-91, Japan

[66] R. D. Saunders and J. B. Shumaker, "Automated Radiometric Linearity Tester," *Appl. Opt.* **23**, 3504-3506 (1984).

[67] These values are from the manufacturer's catalog (obtained Å 1993), Optoelectronic Components Catalog, UDT Sensors, Inc., 12525 Chadron Ave., Hawthorne, CA, USA 90250

[68] J. B. Fowler and G. Dezsi, "High Accuracy Measurement of Aperture Area Relative to a Standard Known Aperture," *J. Res. Natl. Inst. Stand. Technol.* **100**, 277-283 (1995).

[69] G. Eppeldauer, A. L. Migdall, and C. L. Cromer, "Characterization of a High Sensitivity Composite Silicon Bolometer," *Metrologia* **30**, 317-320 (1993).

[70] G. Eppeldauer, A. L. Migdall, and C. L. Cromer, "A Cryogenic Silicon Resistance Bolometer for Use as an Infrared Transfer Standard Detector," *Thermal Phenomena at Molecular and Microscales and in Cryogenic Infrared Detectors*, edited by M. Kaviany et al., (ASME HTD-Vol. 277, New York, NY, 1994), pp. 63-67.

[71] G. Eppeldauer, "Near Infrared Radiometer Standards," *Optical Radiation Measurements III*, James M. Palmer, Editor, Proc. SPIE 2815, pp. 42-54 (1996).

[72] A. L. Migdall and G. Eppeldauer, NIST Measurement Services: Spectroradiometric Detector Measurements: Part III -- Infrared Detectors, Natl. Inst. Stand. Technol., Spec. Publ. 250-42 (in preparation).